TITANIUM FOR CRYOGENIC
PROPELLANT TANKAGE

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Introduction

As part of a continuing program of evaluating high strength materials for possible application in aerospace vehicles, General Dynamics/Astronautics has investigated the mechanical properties of more than fifty metals and alloys. Because of the use of cryogenic propellants such as liquid oxygen (-297°F) in the Atlas ICBM and liquid hydrogen (-423°F) in the Centaur high energy upper-stage vehicle, considerable emphasis has been placed upon determining the behavior of engineering materials at extreme sub-zero temperatures.

Titanium and titanium alloys have for some time been recognized as promising aerospace vehicle materials because of their low density (0.16 lbs. per cu. in. as compared to 0.28 for steel), high strength, excellent corrosion resistance, availability in many forms and shapes, and their ability to be formed and welded by practicable production methods. Titanium is a relative newcomer compared to other engineering metals such as steels, aluminum, and magnesium alloys; its commercial exploitation was long delayed by a combination of high melting point (3135°F), difficulty of extraction from its ores, and because of its high chemical reactivity with many substances at elevated temperatures. Nevertheless, developments in technology led to the founding of a titanium metals industry in 1948, which has progressed since then to the point where at least four major commercial producers have the capacity to supply from 20,000 to 25,000 tons of titanium and titanium alloy mill products annually.

Titanium, like iron, undergoes an allotropic modification, existing as an hexagonal close packed crystal (alpha titanium) at temperatures below 1625°F and as a body centered cubic crystal (beta titanium) at higher temperatures. The addition of alloying elements changes the temperature at which this transformation in crystal structure occurs and also results in the formation of solid solutions and inter-metallic compounds. These effects provide the means for developing wide ranges in mechanical properties through alloying and heat treating. Titanium alloys readily with a large number of metals, producing many useful alloys which may be divided into three classes; all alpha alloys, alpha-beta alloys, and all beta alloys.

The all alpha alloys are characterized by being generally low in strength but very ductile and tough, very weldable, and not amenable to hardening by heat treatment. Aluminum is the most important alpha stabilizing alloy addition. The alpha-beta alloys contain both phases and can be strengthened by heat treatment procedures which changes the amounts of each phase present and which precipitate intermetallic compounds. Manganese, chromium, vanadium, molybdenum, iron, and columbium are the more important beta stabilizing alloying elements. The all beta alloys contain sufficient alloy content to result in a completely beta structure after heat treatment. Alpha-beta alloys possess intermediate strength characteristics and are more or less weldable, with weldability generally poorer in the more highly alloyed conditions. The all beta alloys have the highest strengths with generally low ductility and poor weldability in the high strength condition, but possess excellent ductility, formability, and weldability in the annealed, low strength condition.

Mechanical Property Tests

Approximately one dozen titanium alloys have been investigated at General Dynamics/Astronautics with respect to their mechanical properties at extreme sub-zero temperatures (1), (2). Tests have included determination of their tensile properties (yield and tensile strengths and percent elongation) in both longitudinal and transverse directions, notched tensile strengths, strength and ductility characteristics of fusion welds, cross-tension and shear strengths of individual spot welds; and, for the more promising alloys, fatigue properties of welded joint specimens. These tests have been performed over the temperature range of +78°F to -423°F, with tests performed at room temperature, -100°F (dry ice and alcohol), -320°F (liquid nitrogen), and -423°F (liquid hydrogen).

It has been demonstrated both at Astronautics and by many other investigators that notched tensile tests provide a good criterion of the tendency of thin sheet materials to behave in a brittle manner. When notches are machined in the sides or a transverse slot is milled in the center of tension test specimens, a biaxial stress field is induced when the specimens are loaded. In a ductile material, the effect of the biaxial stress field is to effectively increase the strength of the material since the transverse stresses constrain the metal from deforming and necking, - hence postponing fracture. Thus, in ductile materials, the notched tensile strength exceeds the smooth (uniaxially loaded) tensile strength, and the ratio of notched to un-notched tensile strength exceeds unity. Although the notches act as stress concentrators, a ductile material undergoes some plastic deformation at the roots of the notches, redistributing the stresses, and delaying the initiation of cracks.

In a brittle material, on the other hand, the stress concentrating effect of notches combined with the restricted ability of the material to undergo plastic deformation leads to early crack formation and premature failure of the notched tensile specimen resulting in a lowering of the tensile strength. The notched/un-notched tensile strength ratio of brittle materials will therefore be less than unity. This ratio consequently serves as a useful index of the toughness of high strength sheet alloys.

At any constant test temperature, the notched tensile strength, especially of brittle materials, is markedly influenced by specimen geometry, particularly by the sharpness of the notches. The sharper the notch, and hence the greater its stress concentration effect, the lower will be the notched tensile strength and the notched/un-notched tensile ratio. In addition, in those alloys which undergo a transition from ductile to brittle behavior with decreasing test temperature, the temperature range at which this transition occurs is raised by increases in notch severity.

A large variety of notched tensile specimens have been developed by various laboratories to evaluate the toughness characteristics of metals; ranging from a mildly notched specimen having a stress concentration factor of 3, employed by the Battelle Memorial Institute, to a severely notched specimen having a stress concentration factor of 18, developed by Dr. W. F. Brown, Jr. of the NASA Lewis Laboratories, and recently standardized by ASTM. These tests yield different results when applied to the same material, and therefore all published data on the notched strength characteristics of metals must be carefully evaluated and direct comparisons may be made only when similar test conditions are employed.

As a result of tests performed over a wide range of notch severities, General Dynamics/Astronautics has standardized upon a notched tensile specimen having a stress concentration factor of 6.3 since this specimen yielded an excellent correlation with the fatigue and fracture behavior of both large axially loaded welded joint test specimens and actual 10 feet diameter missile tanks which were subjected to fatigue tests at both ambient and cryogenic temperatures (3). It was also found that this test specimen appeared to yield the best discrimination between materials which behaved in a tough or brittle manner in actual and simulated structures exposed to service conditions. Since a test is useful only to the extent to which it predicts the behavior of materials in real structures, the notched tensile specimen with a stress concentration factor of 6.3 has been extensively employed at Astronautics for evaluating the toughness of high strength sheet alloys.

Titanium For Cryogenic Applications

Of the titanium alloys tested, the all alpha or predominately alpha alloys exhibited the best ductility and toughness characteristics at extreme sub-zero temperatures. The alpha-beta heat treatable alloys displayed intermediate toughness characteristics at cryogenic temperatures. For example, the 6Al-4V-titanium alloy, which is employed in the Atlas helium gas storage bottles, is very tough at temperatures down to -320°F but shows evidence of brittle behavior at -423°F. The all beta titanium alloys, characterized by the 13V-11Cr-3Al-Ti alloy, are extremely brittle at sub-zero temperatures below approximately -60°F.

The all alpha 5Al-2.5 Sn-titanium alloy exhibited the best combination of strength, ductility, and toughness at all test temperatures down to -423°F. This alloy is one of the earliest commercially developed titanium alloys and has been available for almost a decade in the form of sheet, bar, plate and wire. The typical mechanical properties of a commercially produced sheet of the 5Al-2.5 Sn-Ti alloy are shown in Table I. The notched/un-notched tensile ratio is above unity at all temperatures down to -320°F and approaches unity at -423°F; the tensile ductility remains high at all test temperatures, and the weld joint efficiency is 100% down to -100°F, dropping only slightly to 94% at -423°F. A distinguishing characteristic of this and other titanium alloys is that both the yield and tensile strengths increase approximately 100% from room temperature to -423°F. Aluminum alloys may increase in strength from 30% to 60% and steels from 40% to 70% over this temperature range.

Tests performed on several heats of the 5Al-2.5 Sn-Ti alloy made to standard specifications (MIL-T-9047 B-2, ASTM B265-58T grade 6, AMS 4926, etc.) showed a wide range in notched tensile strengths and notched/un-notched ratios at -423°F with some heats having ratios as low as 0.7. These low toughness values were found associated with relatively high contents of oxygen and iron, both of which are normally present as impurities in titanium alloys. Standard specifications permit oxygen contents as high as 0.20% to 0.30% O_2 and iron up to 0.50% Fe. While these levels of oxygen and iron impurities do not embrittle the 5Al-2.5 Sn-Ti alloy at room and moderately elevated temperatures, their embrittling effect becomes noticeable at sub-zero test temperatures and becomes pronounced at -423°F. Carbon, hydrogen, and nitrogen are also present as impurities in titanium alloys but the levels of these elements are generally so low even in commercially produced alloys that they do not embrittle them at cryogenic temperatures.

As the result of a cooperative research program assisted by a number of the titanium producers, the tolerable limits of oxygen and iron which would not embrittle titanium at extreme sub-zero temperatures were determined (4), (5). Based upon tests conducted upon heats of the 5Al-2.5 Sn-Ti alloy containing varying amounts of oxygen and iron, limits of 0.12% maximum oxygen content and 0.25% maximum iron were established. A special specification, GD/A Specification 0-71010, was developed to cover the 5Al-2.5 Sn-Ti sheet alloy intended for cryogenic applications.

The mechanical properties of a heat of 0.014" thick titanium alloy sheet procured to the above specification as shown in Table II. Note that the notched/un-notched tensile ratios at -423°F (1.03 longitudinal and 1.00 transverse) of this material are significantly higher than those of the same alloy procured to commercial specifications. The data shown in Table I actually represent the best of the 5 or 6 commercial heats procured prior to the development of the new specification.

The heat described in Table II was also subjected to notched tensile tests employing the very sharp notched NASA-ASTM specimen, and yielded notched/un-notched tensile ratios at -423°F of 0.65 in longitudinal and 0.68 in transverse tests. These values are almost identical with the sharp-notch ratios of 60% cold rolled Type 301 stainless steel and 2014-T6 aluminum alloy sheet (6). The latter two alloys are currently being used in liquid hydrogen tankage applications (the steel in Centaur and the aluminum alloy in the Saturn S-II and S-IV stages) and are considered to be adequately tough for extreme sub-zero temperature service.

A comparison of the strength-weight characteristics of the 5 Al-2.5 Sn-titanium alloy, 60% cold rolled stainless steel, and 2014-T6 aluminum alloy in both the base metal and weld joint conditions is shown in Table III. Note that the strength-weight ratio of the titanium alloy, both base metal and weld joints, exceeds that of the other alloys at all temperatures, and becomes particularly superior at temperatures of -320°F and lower. The same superiority of titanium in both yield strength/density, and tensile strength/density properties is shown in Figures 1 through 3.

While the detailed data are not presented in this report, extensive shear and cross-tension tests have been performed on individual resistance spot welds in titanium as well as many other alloys. A comparison between the 5Al-2.5 Sn-Ti alloy and the 60% cold rolled Type 301 stainless steel sheet made to GD/A Specification 0-71004 is shown below; both materials being tested in thicknesses in the range of 0.020" to 0.025":

	Average Spot Weld Shear Strength lbs.	Average Spot Weld Cross-Tension Strength, lbs.	Tension/Shear Ratio
301 steel at +78°F	634	486	0.77
5Al-2.5 Sn-Ti at +78°F	1381	360	0.26
301 steel at -320°F	856	164	0.19
5 Al-2.5 Sn-Ti at -320°F	1670	268	0.16

While the cross-tension strengths of spot welds in the titanium alloy and stainless steel are reasonably comparable, the shear strengths of spot welds in titanium are approximately twice that of those in the steel.

During the development of the Atlas missile it was determined that cyclic fatigue tests conducted on axially loaded 4" wide by 36" long welded joint specimens very closely duplicated the fatigue behavior of full scale Atlas propellant tanks incorporating similar weld joint designs. The vertical splice in the Atlas missile tanks is made by heliarc butt-welding the cold rolled Type 301 stainless steel sheet, roll-planishing the weld to smoothen it down to the flat surface of the sheet, and then reinforcing the weld joint by spot welding a doubler sheet, approximately 4" wide, over the weld joint, attaching it by several rows of staggered spot welds placed on both sides of the butt-weld. The doubler sheet is required by the fact that the stainless steel alloy is strengthened by cold working and the butt-weld is of reduced strength due to the annealing effect of the welding heat. The addition of the doubler develops a weld joint having approximately 100% tensile efficiency.

Inasmuch as the 5 Al-2.5 Sn-Ti alloy is already in the annealed condition and is not amenable to hardening by thermal treatment, a simple fusion butt weld joint is essentially as strong as the base metal and no weld reinforcement is necessary to achieve full tensile efficiency.

A comparison of the fatigue resistance of weld joints in titanium and in the 60% cold rolled Type 301 stainless steel is shown in Table IV. The titanium weld joint specimens were tested at stress levels up to 90% of the base metal yield strengths at each test temperature and displayed high fatigue resistance at all temperatures down to -423°F. The steel samples were tested at a stress level of 144,000 psi which represents the maximum flight stresses in the Atlas missile. The data of Table IV demonstrate that, at -320°F, the titanium alloy when stressed cyclically from 0 to 150,000 psi is just as fatigue resistant as the steel stressed from 0 to 144,000 psi, within the limits of the tests conducted. In addition, the -423°F tests show that the titanium alloy when stressed from 0 to 185,000 psi is significantly superior to the stainless steel stressed from 0 to 144,000 psi. Thus, the titanium alloy is comparable in fatigue resistance to the Atlas and Centaur material when tested at -320°F, but is considerably superior at liquid hydrogen temperature. From a fatigue resistance viewpoint, the titanium alloy should be expected to be more reliable than the steel in welded structures exposed to extreme sub-zero temperatures.

It should be borne in mind that the stainless steel has a base metal tensile strength in the range of 300,000 to 320,000 psi at temperatures of -320°F to -423°F while the titanium has a tensile strength of approximately 200,000 psi at -320°F and 250,000 psi at -423°F. Consequently when weld joints are loaded to the same stress levels in both materials, the titanium alloy is considerably more severely loaded; i. e. stressed at a higher preportion of its yield and tensile strengths. Nevertheless, the titanium alloy displays a higher fatigue resistance and greater structural integrity than the stainless steel.

Availability of Titanium Alloy Sheet

Up to recently, the 5 Al-2.5 Sn-Ti alloy was available in wide sheet form only as hand rolled sheet approximately 36" wide by 96" to a maximum of 180" in length, with some sheet being produced up to 48" in width. The minimum thickness to which wide sheet was rolled was 0.025", while thinner sheet down to foil gauges was available in coiled strip form in widths up to approximately 12". The commercial thickness tolerance was ± 0.002" for sheet 0.008" to 0.016" in thickness, ± 0.003" for sheet 0.017" to 0.026" in thickness, and ±0.004" for sheet 0.027" to 0.040" in thickness.

For application to missile tankage, Astronautics desires sheet up to 36" in width in coil form, to thickness tolerances of one-half the commercial tolerances, and to flatness and camber tolerances considerably tighter than normal commercial requirements. These new requirements are reflected in GD/A Specification 0-71010, "Titanium Alloy Sheet, 5Al-2.5 Sn, Annealed." The four major producers of titanium were contacted regarding the possibility of providing the 5Al-2.5 Sn-Ti alloy in coil form in widths up to 36" and thicknesses down to 0.010" and to the thickness, flatness, and camber tolerances, chemical analysis, and mechanical properties specified in GD/A Spec. 0-71010.

While none of the producers could guarantee meeting the GD/A requirements, it was their general opinion that it was technically feasible to produce the alloy in the form required and that some development work would be necessary before they could safely guarantee meeting the requirements. It was decided to place a trial order with one producer to provide several hundred pounds of 0.015" thick coil sheet 24" in width. The Republic Steel Corp. accepted this order and delivered a 77 foot length of 18-3/4" wide sheet, 0.014" in thickness in May 1961 (7). The reduced width resulted from edge cracks which required trimming the sheet to a narrowerwidth than was desired. The supplier attributed the problem of edge cracking to improper processing of the sheet in earlier reduction passes and was convinced that it was not inherent in the material. The mechanical properties of this material at room and cryogenic temperatures were excellent, reference Table II, and justify the requirements for low oxygen and iron contents.

The appearance of the 77 foot coil supplied by the Republic Steel Corp. is shown in Figures 4 and 5. The sheet was rolled in a Sendzimir mill and achieved a very smooth surface finish and uniform thickness. Measurements made across the width and along the full length showed an average thickness of 0.014" with a minimum of 0.0136" and a maximum of 0.0145." Other suppliers have initiated in-house development programs aimed at producing wide, thin gauge coil sheet from the 5 Al-2.5 Sn-Ti alloy melted to have low impurity levels and capable of meeting all requirements of GD/A Spec 0-71010. These industrial sponsored programs have developed to the point where, by the end of 1961, the titanium producers have expressed a willingness to guarantee the production of 36" wide sheet down to 0.010" gauge with a 12-16 week delivery schedule.

A second order for 600 lbs. of 24" wide 0.015" thick coil stock of the 5 Al-2.5 Sn-Ti alloy has been placed with the Republic Steel Corp. and delivery of the material is expected by Dec. 20, 1961. The material may actually be delivered in a width greater than 24" since the sheet stock has been successfully rolled down in hot bands 28" in width with little or no edge cracking requiring trimming. This material is intended for the fabrication of a 10 foot diameter test tank under a General Dynamics/Astronautics sponsored research and development program.

Fabrication of Titanium Alloy Sheet

The production of missile tankage and hardware from the 5 Al-2.5 Sn-Ti alloy will require the conduct of bending, stretch-forming, deep drawing, and welding operations, the latter including fusion butt-welding, resistance spot welding and overlapping spot seam welding.

The Atlas and Centaur bulkheads are fabricated by butt-welding together a number of stretch formed pie-shaped gore sections. Each gore section is individually stretch formed from a 1/2 or 3/4 hard cold rolled Type 301 stainless steel sheet 36" wide and approximately 10 feet in length. The stretch-forming is performed on a Cyril Bath machine, with the sheet pulled from one end while in contact with the lubricated die surface, the forming being done at room temperature. Up to the present time, four gore sections for the Atlas intermediate bulkhead have been successfully stretch-formed in the existing Atlas tooling from 0.025" to 0.040" thick 36" wide by 144" long sheet of commercial quality 5 Al-2.5 Sn-Ti alloy. This stretch-forming was accomplished at room temperature with no change in normal production practice employed for stretch-forming of steel detail parts.

Figure 6 shows the stretch-forming of a sample cut from the 0.014" thick, 18 3/4" wide coil stock of 5 Al-2.5 Sn-Ti alloy made by the Republic Steel Corp. This material stretch-formed very successfully. All gore sections were rough trimmed after stretch-forming and placed back on the double curvature die face to determine if spring back or other distortion had occurred. It was found that the stretch-formed titanium alloy gores evidenced less spring-back, if any, than regular production stainless steel gores. Figure 7 shows two of the rough trimmed titanium alloy gore sections. While the double curvature of these parts is not evident in the photograph, the amount of curvature is considerable, particularly in the longitudinal direction.

Figure 7 also shows some of the 4" wide by 36" long fatigue test specimens made from the 5 Al-2.5 Sn-Ti alloy. The one on the left has a simple heli-arc fusion butt weld and the one on the right is a lap weld joint, with an overlapping spot seam weld reinforced with one row of spot welds spaced every 1/2" apart on each side of the seam weld.

Insofar as welding of titanium alloy sheet is concerned, only slight modification of existing Atlas and Centaur tooling is required for fusion welding. The prime requirement is for greater inert atmosphere shielding of both the face and back surfaces of the sheet in the area being welded as well as trailing shields to prevent contamination of the weld zone during cooling from the welding heat. Figure 8 shows experimental fusion butt-welds which were made in a stretch-formed gore section which had been cut into strips and welded together. The weld joints were radiographed after welding and were found to be sound and free of cracks and porosity. The gore sections shown in Figure 8 were approximately 3 feet wide by 4 feet in length.

Spot welding of titanium offers no difficulties and can be and is being satisfactorily performed on existing tooling with no modification in procedure other than minor changes in weld schedules.

Plans For Future Work

As previously outlined, additional material is being procured for the experimental fabrication of a 10 foot diameter tank with one titanium alloy bulkhead. A second bulkhead of heavy gage stainless steel will be bolted to the tank and the tank will be fatigue and burst pressure tested at room temperature. This program is underway under a General Dynamics/Astronautics sponsored investigation.

Tests are also underway to obtain more data on the static tensile and fatigue resistance characteristics of a variety of weld joint designs to determine optimum weld joint designs and establish design allowable stresses for titanium and titanium weldments.

It is hoped to extend this work to include the fabrication of tanks fitted with attachments such as bosses, flanges, welded-on brackets, etc., and test titanium alloy tanks under both static and cyclic fatigue loading at cryogenic temperatures. Such tests are required to prove that titanium can be successfully employed as a structural material in light-weight cryogenic propellant missiles and spacecraft.

Reactivity of Titanium With Cryogenic Propellants

Because of the increased chemical reactivity of titanium as compared to other structural metals such as steels and aluminum alloys, the question of compatibility of titanium with liquid propellants arises. While some cases of combustion reactions between titanium and oxygen have been reported, there exists much conflicting information; and it is known that there are several successful applications in high speed aircraft and missiles where titanium pressure vessels are used in conjunction with both gaseous and liquid oxygen. In the Titan ICBM, for example, the helium gas required for pneumatic systems is stored in 2 foot diameter spherical pressure vessels made from the 6Al-4V-titanium alloy; the vessels being located in the liquid oxygen tank to chill them and increase their gas storage capacity.

A number of accident incidents have been reported where titanium piping used in oxygen lines ignited and burnt, but similar incidents have also occurred where stainless steel lines used in a high pressure gaseous oxygen line burnt when an explosion occurred in the system. It is a well known fact that practically all metals will burn in an oxygen atmosphere once sufficient heat is generated to start the combustion.

In an effort to accumulate information on the reactivity hazard, surveys were made by General Dynamics/Astronautics of the available literature on the compatibility of titanium with liquid and gaseous oxygen (a) and liquid and gaseous fluorine (b).

As a result of the surveys it was concluded that, under certain conditions of compressive impact, titanium and its alloys can be made to react violently with liquid or gaseous oxygen and fluorine. The reaction is highly exothermic and in some instances may proceed until either the titanium or the oxygen is entirely consumed. The mechanism of the reaction of titanium with oxygen appears to depend upon the following (a):

a. Initiation of the reaction requires an input of high, local energy such that the temperature of the reactants can reach some high threshold value at the local area;

b. the reaction proceeds only when the oxygen is in the gaseous condition; but, of course, this may be readily generated, as by the highly localized heat of compressive impact;

c. the gaseous oxygen, present or generated on the surface by the heat of impact, must be compressed and brought into intimate contact with the titanium surface;

(a) GD/A Report MRG-232, "Compatibility of Titanium and Titanium Alloys with Liquid and Gaseous Oxygen in Missile Propellant Systems," 7 June 1961.

(b) GD/A Report MRG-259, "Compatibility of Titanium and Titanium Alloys with Liquid and Gaseous Fluorine," 11 September 1961.

d. the force which generates the heat, i.e. compressive impact, must also expose a fresh, unoxidized surface on the titanium which can then react with the compressed gaseous oxygen.

Thus according to this explanation, several conditions must be met at approximately the same instant to initiate and propagate the titanium-liquid oxygen reaction. These conditions are met in the ABMA-NASA-type compressive impact test, but are not met in the several other somewhat more practical tests conducted. It may be noted, too, that presence of grit, foreign material, rough surfaces, etc. would increase "impact sensitivity" by creating the condition for high local friction to initiate the reaction, as explained above.

To obtain more definitive data on the extent and possible seriousness of the titanium-oxygen reactivity hazard, the Titanium Steering Committee which was established by NASA approved a series of test programs on the reactivity problem which are to be completed by 1 January 1962 (c). These test programs encompass a wide series of tests, of which the following are the most significant:

1. Puncture of titanium diaphragms with pressurized gaseous and liquid oxygen in test chambers.

2. Detonation of pyrotechnic devices near titanium in contact with gaseous and liquid oxygen.

3. Impact of high velocity simulated micrometeoroid particles against pressurized titanium diaphragms in contact with gaseous and liquid oxygen.

4. Spark sensitivity, thermal initiation, and orifice flow tests involving titanium and liquid and gaseous oxygen.

5. Fatigue and crack propagation tests on titanium immersed in liquid oxygen.

6. Evaluation of protective coatings and treatments applied to titanium to reduce reactivity with oxygen.

The outcome of the above tests will determine the applicability of titanium to thin-skinned tankage for liquid oxygen.

There is no reactivity hazard insofar as liquid hydrogen is concerned and titanium is completely suitable for application in thin-skinned tankage and propellant lines for liquid hydrogen. If tests demonstrate that titanium is unsuitable for use in liquid oxygen tankage, it is then feasible to design and fabricate the liquid

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(c) "Titanium/Centaur Steering Committee Report, Meeting No. 1, "W. A. Richl, George C. Marshall, Space Flight Center, Huntsville, Ala. 20 Nov. 1961.

hydrogen tanks from titanium and the liquid oxygen tanks from cold rolled stainless steel and still achieve a significant weight reduction over a completely steel missile in a Centaur-type vehicle. The very low density of liquid hydrogen as compared to liquid oxygen necessitates a liquid hydrogen tank many times greater in volume than the liquid oxygen tank so that the weight of the liquid hydrogen tank accounts for a major portion of the total tankage weight.

REFERENCES

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3. A. Hurlich, "Summary of Symposium on Low Temperature Properties of High-Strength Aircraft and Missile Materials," ASTM Special Technical Publication No. 287. 1960, p 215-225.

4. GD/A Report No. MRG-262, "Determination of the Effects of Iron and Oxygen Contents on the Mechanical Properties of Ti-5Al-2.5 Sn Alloy Sheet at Liquid Hydrogen Temperature," 5 October 1961.

5. GD/A Report No. MRG-266, "Determination of the Effect of Oxygen Content on the Mechanical Properties of Ti-5Al-2.5 Sn Alloy at Room and Cryogenic Temperatures," 20 October 1961.

6. G. B. Espey, M. H. Jones, and W. F. Brown, Jr. "Sharp-Edge-Notch Tensile Characteristics of Several High-Strength Titanium Sheet Alloys at Room and Cryogenic Temperatures," ASTM Special Technical Publication No. 287, 1960, p 74-95.

7. GD/A Report No. MRG-234, "Evaluation of Coil of Cold-Rolled and Annealed Titanium Alloy Strip, Ti-5Al-2.5 Sn, Produced by Republic Steel Corp., Heat No. 3930131," 14 June 1961.

TABLE I

Mechanical Properties of 5 Al-2.5 Sn-Titanium Alloy Sheet (1)

Test Temp °F	Grain Direction	Yield Strength psi	Tensile Strength psi	Elong. % in 2"	Notched Tensile Strength, psi K_t=6.3	Notched/ Unnotched Ratio	Heli-arc Butt Weld, Tensile Strength psi	Weld Elong. % in 2"	Weld Joint Efficiency %
+78	Long.	113,000	118,000	19	158,000	1.34	121,000	12	100
+78	Trans.	115,000	120,000	14	159,000	1.33	-	-	-
-100	Long.	135,000	142,000	18	175,000	1.23	142,000	11	100
-100	Trans.	137,000	144,000	11	-	-	-	-	-
-320	Long.	184,000	196,000	15	226,000	1.15	192,000	8	98
-320	Trans.	185,000	199,000	11	220,000	1.11	-	-	-
-423	Long.	230,000	247,000	15	239,000	0.97	233,000	4	94
-423	Trans.	230,000	244,000	11	208,000	0.85	-	-	-

(1) 36" x 96" x 0.040" thick commercial quality material, TMCA Heat # M-8465, mill annealed.

Longitudinal values are averages of 5 tests, transverse values are averages of 2 tests at each temperature.

TABLE II

Mechanical Properties of 5 Al-2.5 Sn - Titanium Alloy Sheet[(1)]

Test Temp °F	Grain Direction	Yield Strength psi	Tensile Strength psi	Elong. % in 2"	Notched Tensile Strength psi K_t=6.3	Notched/ Unnotched Ratio K_t=6.3	Notched Tensile Strength psi K_t=18	Notched/ Unnotched Ratio K_t= 18
+78	Long.	118,500	127,700[(2)]	14.5	169,000[(2)]	1.32	148,200[(3)]	1.16
+78	Trans.	118,600	125,600	14.2	167,500	1.33	150,400	1.20
-423	Long.	228,700	240,500	11.0	247,400	1.03	155,200	0.65
-423	Trans.	227,700	237,300	11.3	237,300	1.00	161,500	0.68

(1) 18 3/4" wide x 77 feet long coil, 0.014" thick sheet, Republic Steel Corp. Heat # 3930131 chemical composition:

Al	Sn	Fe	C	N_2	O_2	H_2
5.45	2.50	0.11	0.035	0.011	0.12	0.0099

(2) Average of three tests

(3) Average of two tests

TABLE III

Strength - Weight Characteristics of High Strength Sheet Alloys

Alloy	Density lbs/in.^{3}	Test Temp °F	Tensile Strength psi	Strength-Density Ratio, x 10^{-6}	Weld Joint Description	Tensile Strength of Weld, psi	Weld Strength-Density Ratio, x 10^{-6}
Aluminum Alloy 2014-T6	0.100	+78	73,000	0.73	0.063" sheet with fusion	53,000	0.53
	"	-100	76,000	0.76	weld, 2319 filler metal,	56,700	0.567
	"	-320	87,000	0.87	weld bead not removed.	62,000	0.62
	"	-423	104,000	1.04		75,600	0.756
60% Cold Rolled Type 301 Stainless Steel	0.290	+78	224,000	0.77	0.020" sheet	220,000	0.76
	"	-100	243,000	0.84	heli-arc butt	-	-
	"	-320	316,000	1.09	weld, roll planished,	250,000	0.86
	"	-423	322,000	1.11	spot welded doubler	225,000	0.78
5Al-2.5 Sn Titanium Alloy	0.161	+78	124,000	0.77	0.040" sheet	121,000	0.75
	"	-100	145,000	0.90	heli-arc butt weld, no roll	142,000	0.88
	"	-320	198,000	1.23	planishing, no doubler.	192,000	1.19
	"	- 423	250,000	1.55		233,000	1.45

TABLE IV

Fatigue Resistance of Weld Joints

A. 5 Al-2.5 Sn - Titanium Alloy Sheet (1)
(0.027" Thick Sheet, TMCA Heat No. M-9048)

Test Temp°F	Cyclic Stress Range	No. of Cycles to Failure	Results
+78	0-100,000 psi	2000	No failure or cracks (2 tests, Test stopped
-320	0-150,000 psi	2000	No failure or cracks (2 " Test stopped
-423	0-150,000 psi	2000	No failure or cracks (1 test Test stopped
-423	0-150,000 psi	1051	Failed in grip (1 test)
-423	0-150,000 psi	1528	Failed in grip (1 test)
-423	0-185,000 psi	1143	Failed in weld (1 test)
-423	0-185,000 psi	1426	Failed in grip (1 test)
	(0.020" Thick Sheet, Reactive Metals Heat No. 31387)		
+78	0-100,000 psi	2000	No failure or cracks (1 test) Test stopped
-320	0-162,000 psi	2047	No failure or cracks (1 test) Test stopped
-320	0-162,000 psi	1451	Failed in grip (1 test)
-320	0-162,000 psi	1332	Failed in grip (1 test)
-423	0-205,000 psi	539	Failed in grip (1 test)
-423	0-205,000 psi	113	Failed in grip (1 test)

B. Type 301 Cold Rolled Stainless Steel Sheet (2)
(0.020" Thick Sheet, Washington Steel Co. Heat No. 48081)

Test Temp°F	Cyclic Stress Range	No. of Cycles to Failure	Results
+78	0-144,000 psi	934	Average of 5 tests
-320	0-144,000 psi	2671	Average of 5 tests
-423	0-144,000 psi	633	Average of 5 tests

(1) 4" wide x 36" long specimens with transverse heli-arc butt weld joint, as welded with no roll-planishing or weld reinforcement and no doubler attached. Specimens axially loaded 6 cycles per minute.

(2) 4" wide x 36" long specimens with transverse heli-arc butt weld joint, weld roll-planished, reinforced with doubler having 4 rows of spot welds on each side of butt-weld. Sheet procured to GD/A Spec. 0-71004, 207,000 psi yield strength, 223,000 psi tensile strength at +78°F.

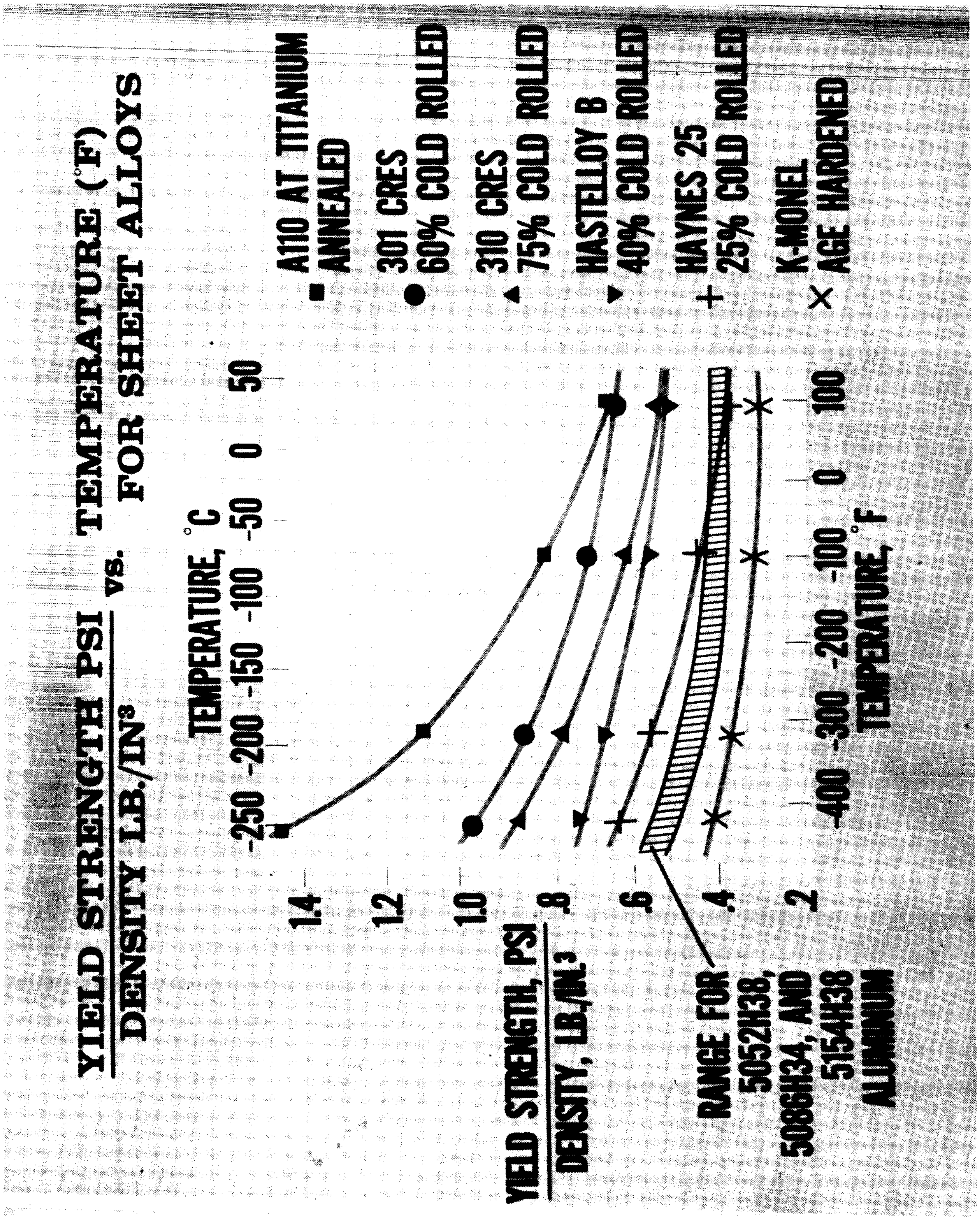
YIELD STRENGTH PSI / DENSITY LB./IN³ vs. TEMPERATURE (°F) FOR SHEET ALLOYS
TEMPERATURE, °C
-250 -200 -150 -100 -50 0 50
YIELD STRENGTH, PSI / DENSITY, LB./IN.³
1.4
1.2
1.0
.8
.6
.4
.2
-400 -300 -200 -100 0 100
TEMPERATURE, °F
RANGE FOR 5052H38, 5086H34, AND 5154H38 ALUMINUM
A110 AT TITANIUM ANNEALED
301 CRES 60% COLD ROLLED
310 CRES 75% COLD ROLLED
HASTELLOY B 40% COLD ROLLED
HAYNES 25 25% COLD ROLLED
K-MONEL AGE HARDENED

Figure 1

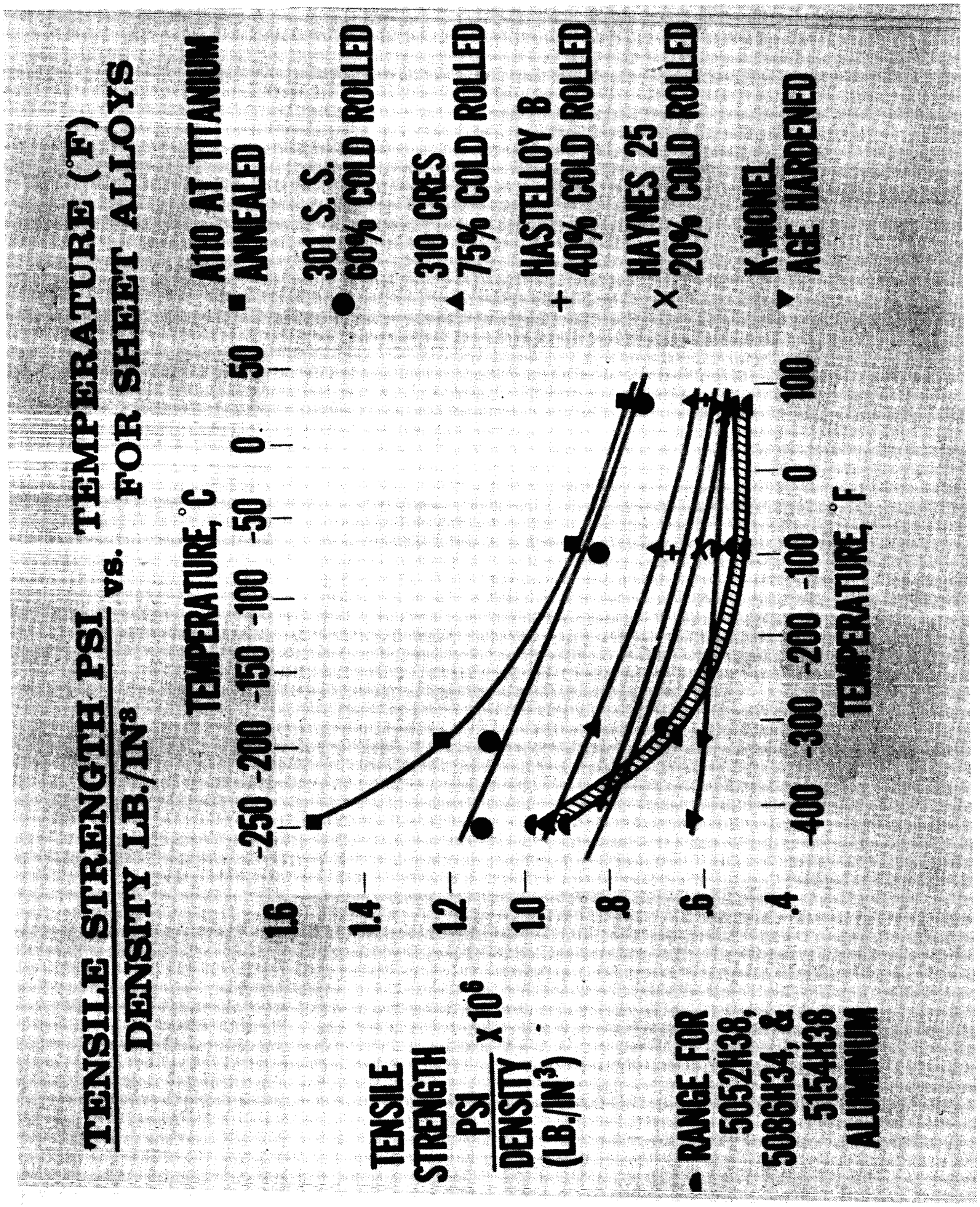
TENSILE STRENGTH PSI / DENSITY LB./IN³ vs. TEMPERATURE (°F) FOR SHEET ALLOYS
TENSILE STRENGTH PSI / DENSITY (LB./IN³) x 10⁶
TEMPERATURE, °C
-250 -200 -150 -100 -50 0 50
1.6
1.4
1.2
1.0
.8
.6
.4
-400 -300 -200 -100 0 100
TEMPERATURE, °F
■ A110 AT TITANIUM ANNEALED
● 301 S. S. 60% COLD ROLLED
▲ 310 CRES 75% COLD ROLLED
+ HASTELLOY B 40% COLD ROLLED
× HAYNES 25 20% COLD ROLLED
▼ K-MONEL AGE HARDENED
RANGE FOR 5052H38, 5086H34, & 5154H38 ALUMINUM

Figure 2

STRENGTH-DENSITY RATIOS OF HIGH STRENGTH SHEET ALLOYS (BASE METAL PROPERTIES)

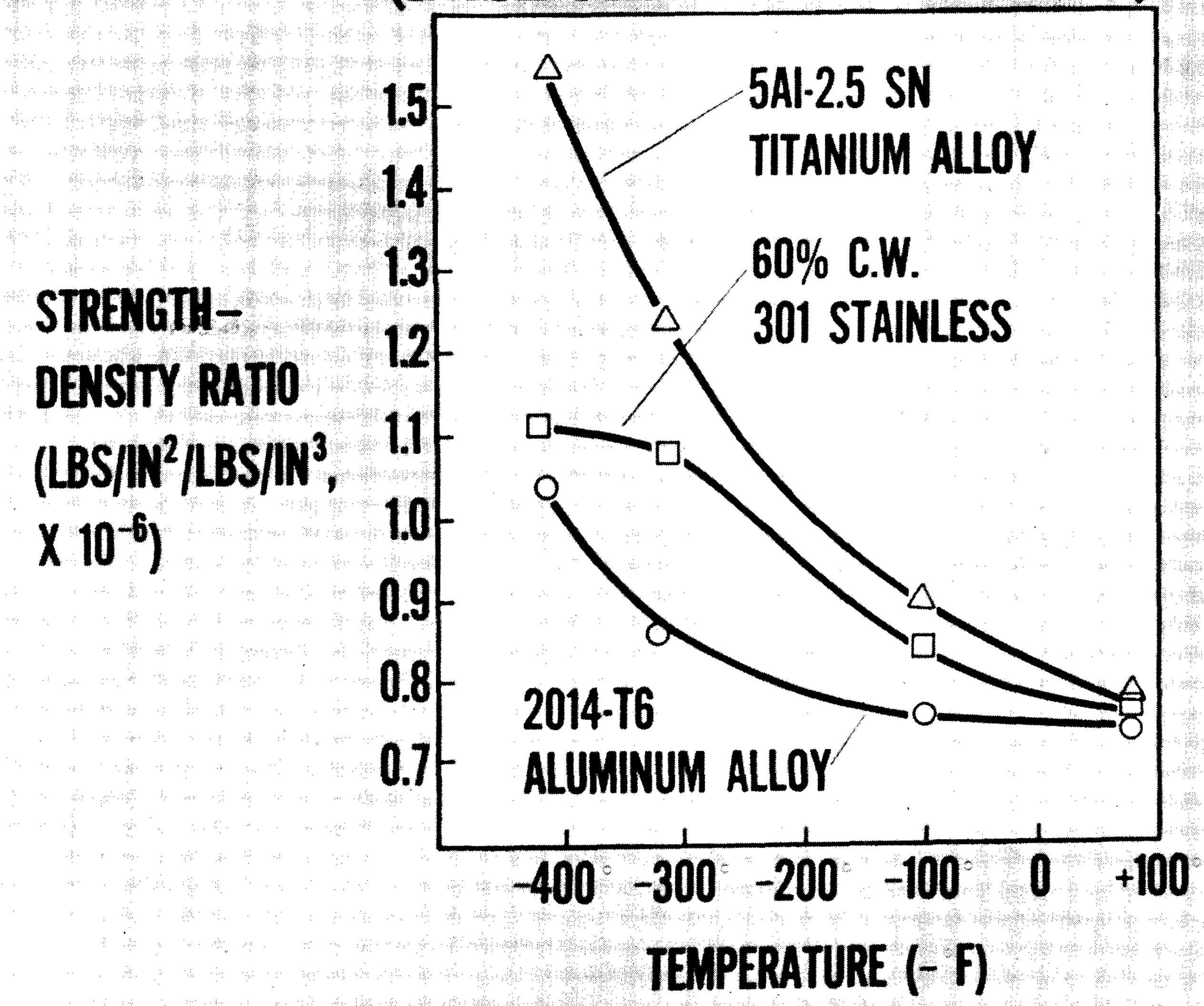

Figure 3

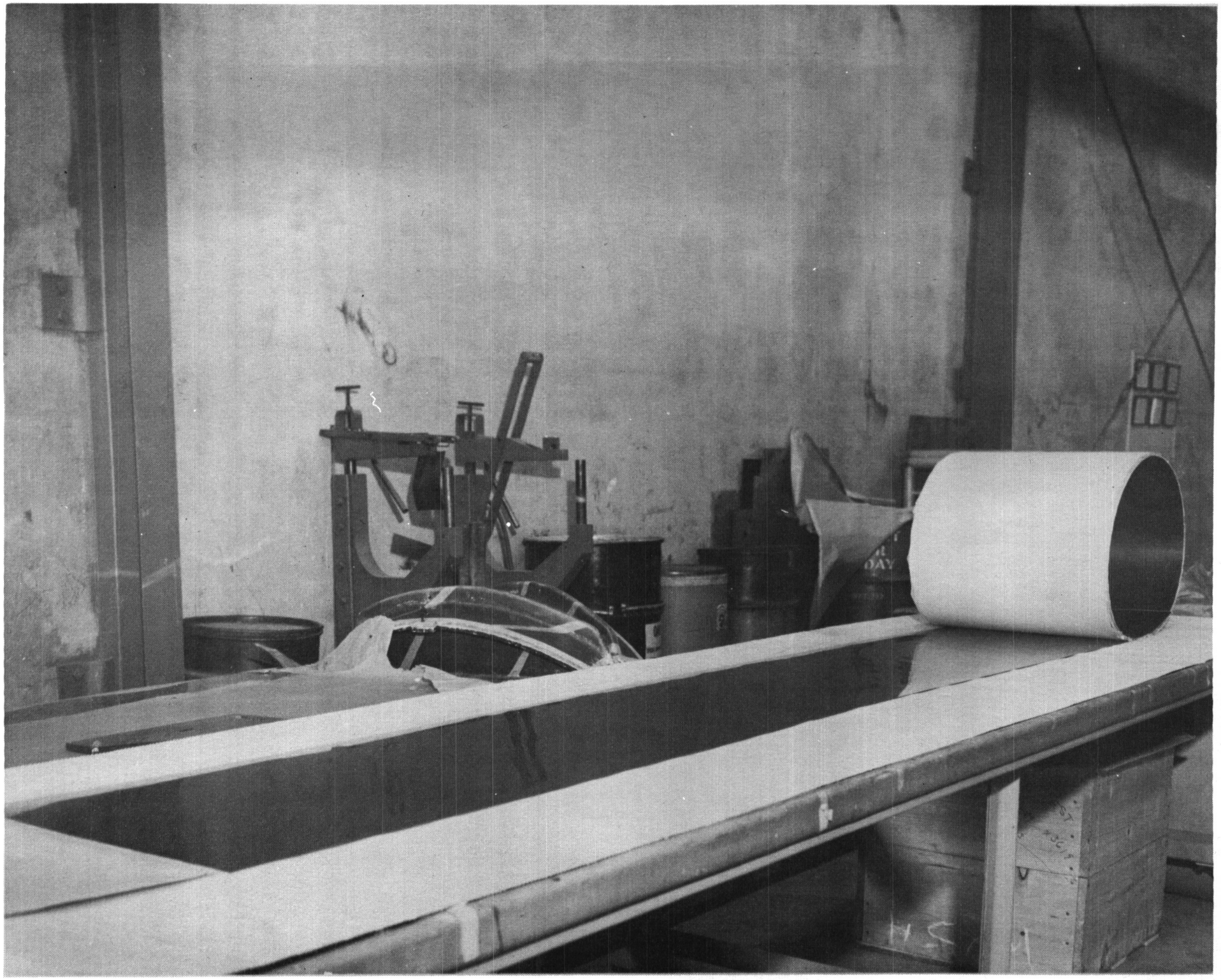

Figure 4 - Coil of 18 3/4" wide by 77 feet long of 0.014" thick 5Al-2.5Sn-Ti alloy produced by Republic Steel Corp.

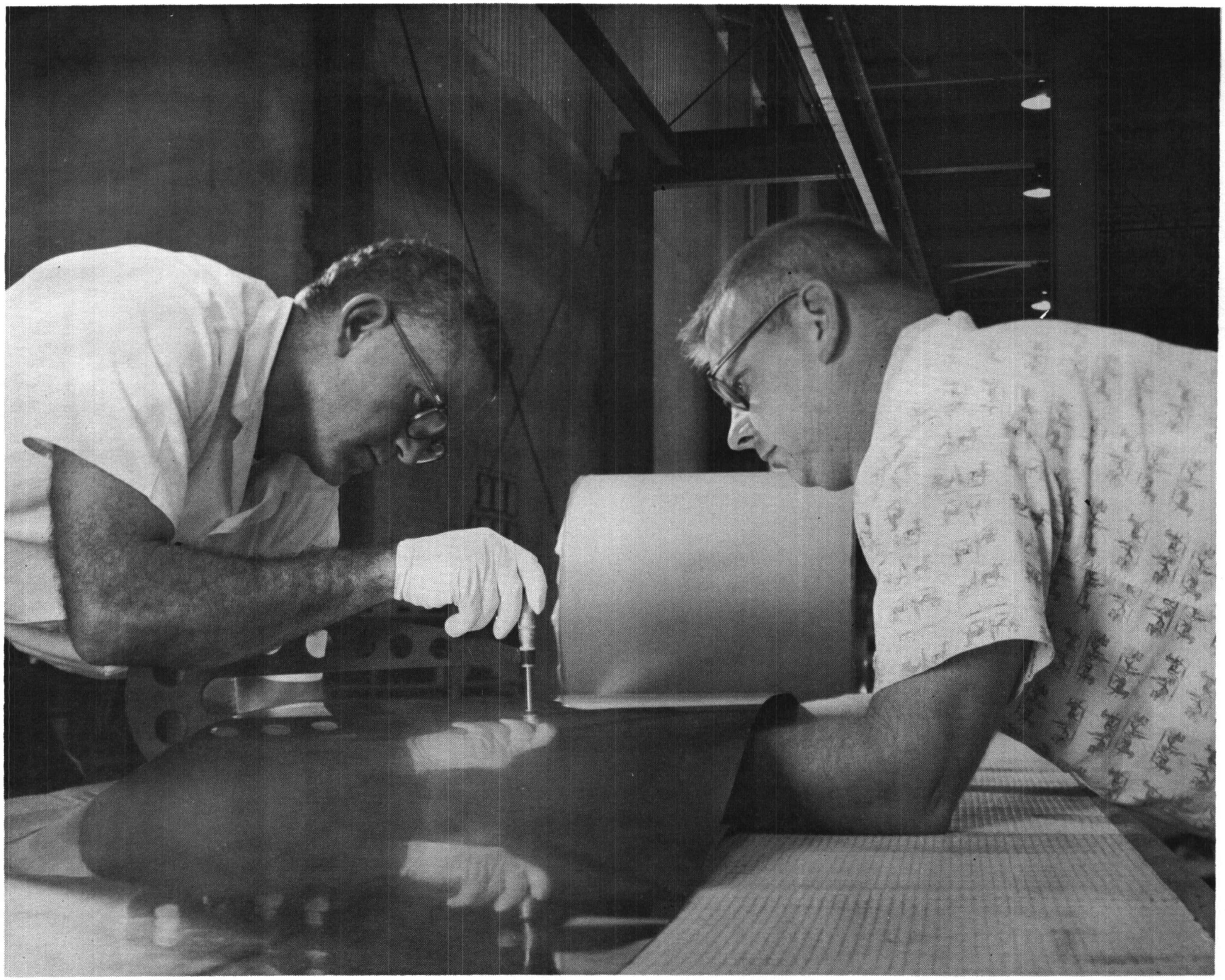

Figure 5 - Measuring thickness of 5Al-2.5Sn-Ti alloy Sendzimir rolled sheet. Note high reflectivity and smooth surface of sheet.

Figure 6 - Stretch-forming bulkhead gore from 0.014" thick, 18-3/4" wide sheet of 5Al-2.5Sn-Ti alloy on tooling for Atlas fabrication. Cyril Bath stretch-former.

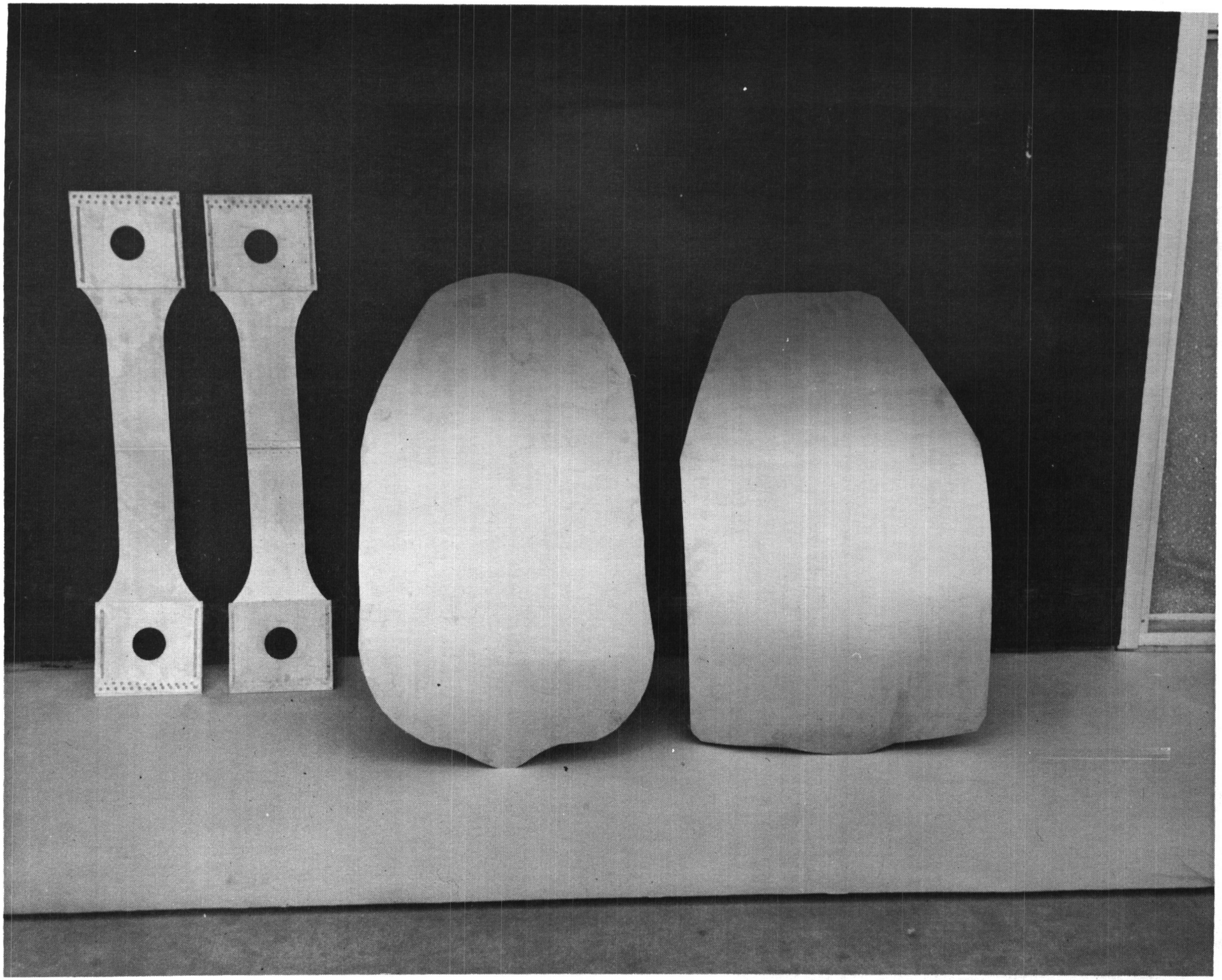

Figure 7 - Rough trimmed stretch-formed gores made from 0.025"-0.040" thick commercial quality 5 Al-2.5Sn-Ti alloy sheet. At left are two weld joint fatigue test specimens 4" wide in test area and 36" in length.

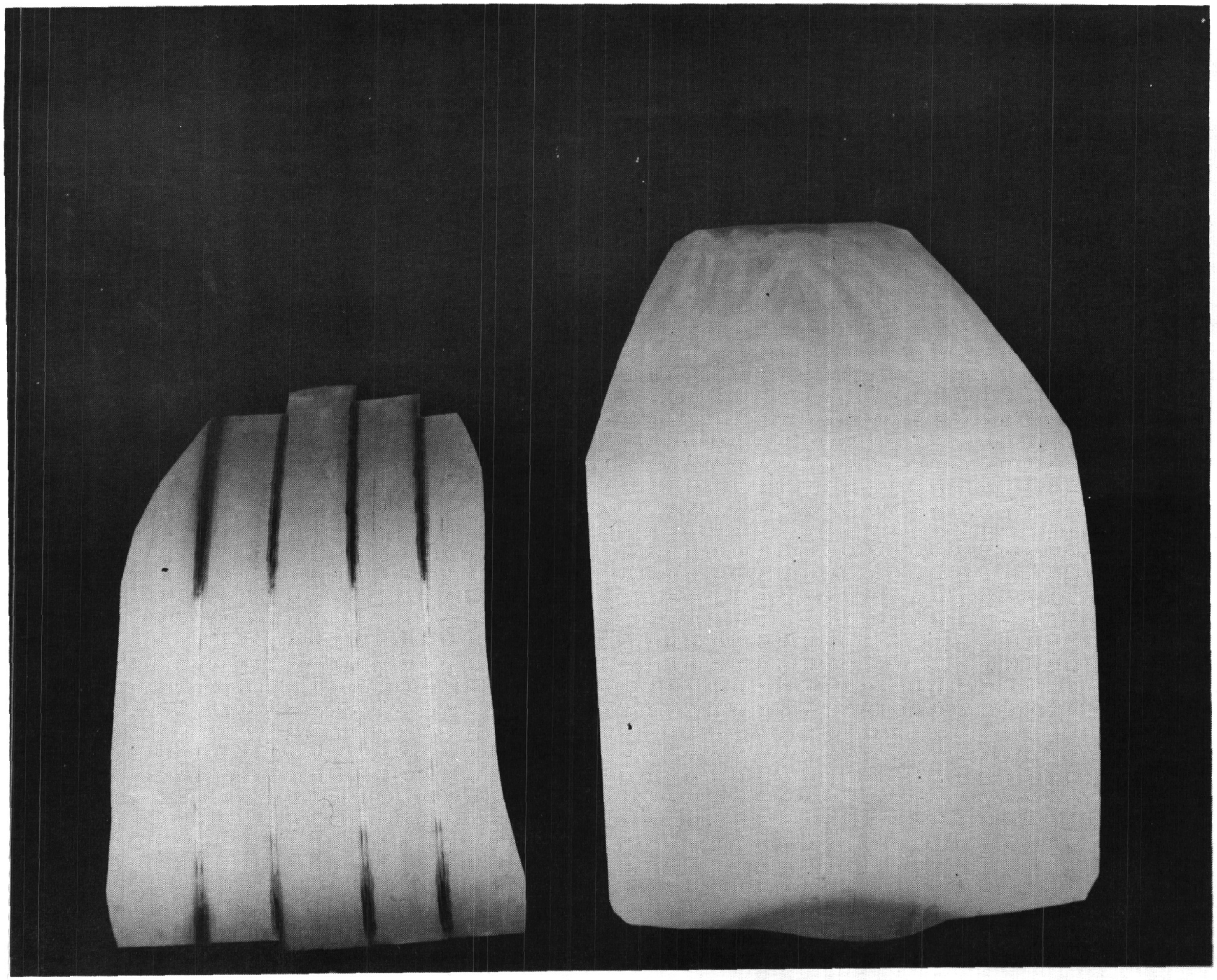

Figure 8 - Right - Stretch-formed gore 36" x 48" in size.
Left - Gore cut into strips and fusion welded.